Food Irradiation Economies of Scale in a Developing Country Context*

Rosanna Mentzer Morrison.
Economic Research Service, U.S. Department of Agriculture
Washington, D.C., United States of America

Introduction

Food irradiation technology is considered capital intensive.
Building a commercial scale irradiator requires a substantial
investment in special shielded structures, conveyor machinery,
and source material. Analysts have asserted that because of
this high investment, large quantities of food must be treated
to achieve reasonable average unit costs [1]. Generally, capital
intensive technologies requiring high volumes are not compatible
with a developing country's resource base. This paper examines
the economies of scale in single purpose, cobalt-60 food
irradiators to evaluate how the size of an irradiator, and the
level of labor costs and capital charges, affect treatment
costs.

The term economies of scale refers to the relationship be-
tween total average costs per unit of output (unit costs) and
the size of the plant. Economies of scale exist if unit costs
fall as size increases. If economies of scale exist, large
irradiators would be able to treat foods at a lower unit cost
than smaller ones. Operators of small irradiators would be at
a distinct cost disadvantage if the scale economies are substantial.
This would discourage an industry of small volume, widely-scattered
agricultural firms from using the technology.

A question of interest to potential users of irradiation
technology, then, is how important is the size of an irradiator
and its corresponding throughput to the average cost of the
treatment. Can only the very largest irradiators realize
reasonable unit costs? Are their costs substantially lower than
those of smaller plants? A related question is how severe are
the cost penalties for running an irradiator at less than
capacity.

Previous research using labor rates, construction costs,
and other input prices representative of the United States,
found economies of scale for cobalt-60 irradiators to be pronounced
at smaller sizes and less important at medium and large sizes
[2]. Irradiators handling annual volumes less than 22.5
million kilograms could not achieve the lower unit costs possible
for larger irradiators. In this paper, the author explores how
economies of scale for cobalt-60 irradiators are affected under
input prices more typical of a developing country.
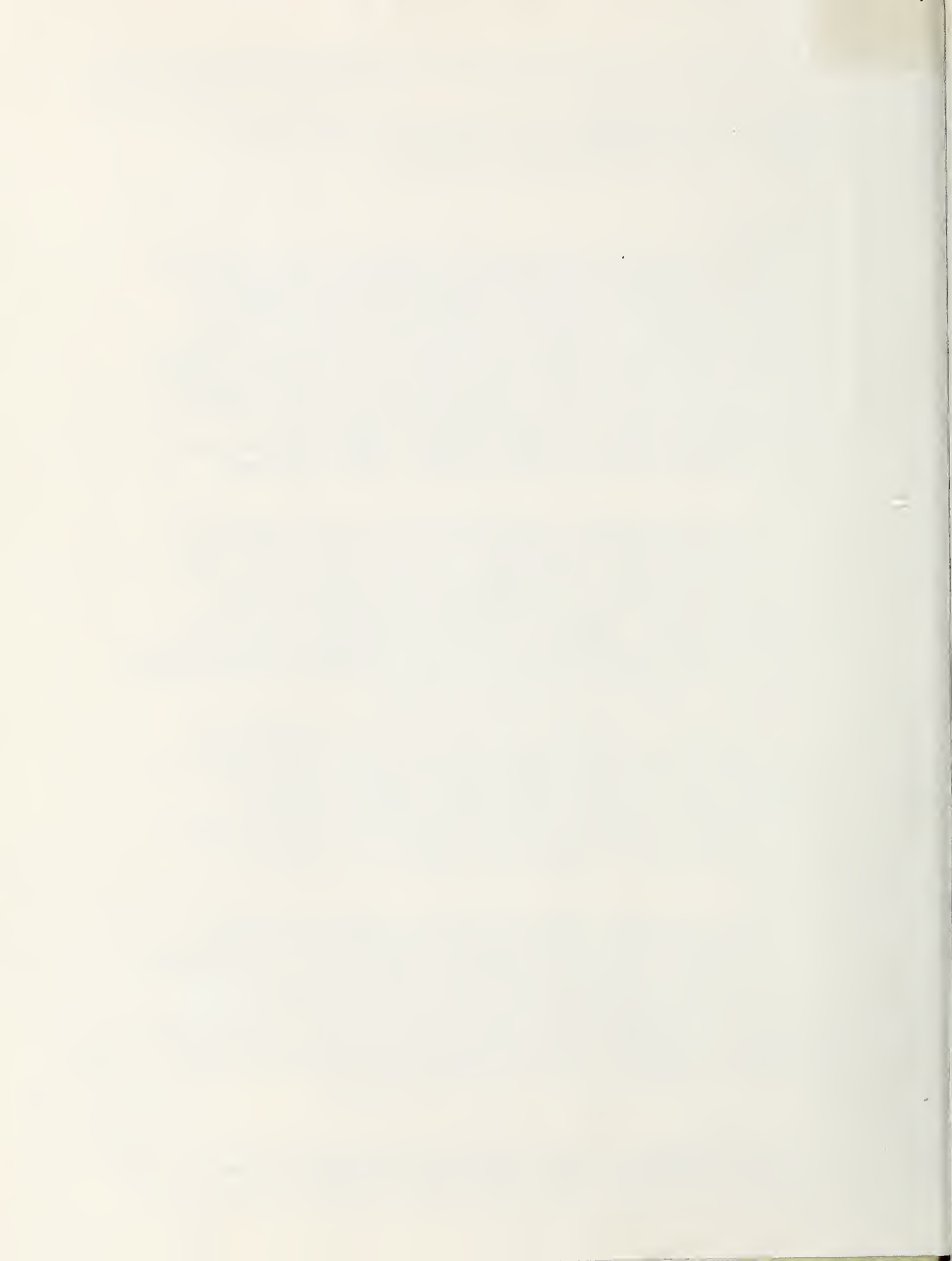
The scale, or size, of a plant is determined by its hourly throughput. Costs were calculated for irradiators designed to treat 1,500; 3,000; 6,000; 9,000; and 12,000 kilograms of food per hour 1/. Irradiation treatment costs were also estimated for four dose levels: 0.1, 0.25, 0.5, and 2.5 kGy. These dose levels correspond to irradiation applications ranging from sprout inhibition to pathogen reduction. Costs were estimated for single purpose irradiators to illustrate the lower costs possible with an in-house facility dedicated to treating one product for a specific purpose 2/.

Major Assumptions

Irradiator design and operation are very specific to the particular food, its reaction and tolerance to radiation, relative prices of capital and labor, and other factors unique to each developing country's economy and resource base. However, development of cost relationships by plant size requires specific assumptions about input prices and operating procedures to provide the standardization needed to make interplant cost comparisons. Capital and operating costs were estimated for the model irradiators based on information from builders and operators of commercial irradiation facilities. Reliance on their judgement and experience was essential because of the lack of single purpose food irradiators from which to collect empirical data. The costs presented here are meant to provide the reader with an idea of the magnitude of irradiation treatment costs and how these generalized costs might vary with plant size.

The major assumptions underlying the estimated unit costs are identified below.

1) Irradiators do not operate continuously. Downtime must be allowed for maintenance and source loading. In this analysis, irradiators were assumed to require 1 hour downtime for every 7 hours of processing. For example, during a 24-hour processing day, the irradiator would treat products for 21 hours. The annual volumes in this analysis are based on 250 processing days per year.

2) Net utilization efficiency of the cobalt-60 was assumed to be 25 percent for all irradiators. Net utilization efficiency is the percent of emitted energy absorbed in the product. It is one of the parameters which determines how much cobalt-60 is needed. Under actual conditions, this efficiency depends on the design of the irradiator, which must consider the product's density and dose uniformity needs.

1/ This translates to annual volumes of approximately 7.9, 15.8, 31.5, 47.3, and 63 million kilograms, respectively, when plants are operated three shifts for 250 days per year.

2/ Another approach would be to irradiate foods in a multi-purpose irradiator. However, the flexibility needed to handle diverse products receiving different doses sacrifices efficiency and increases costs [3].
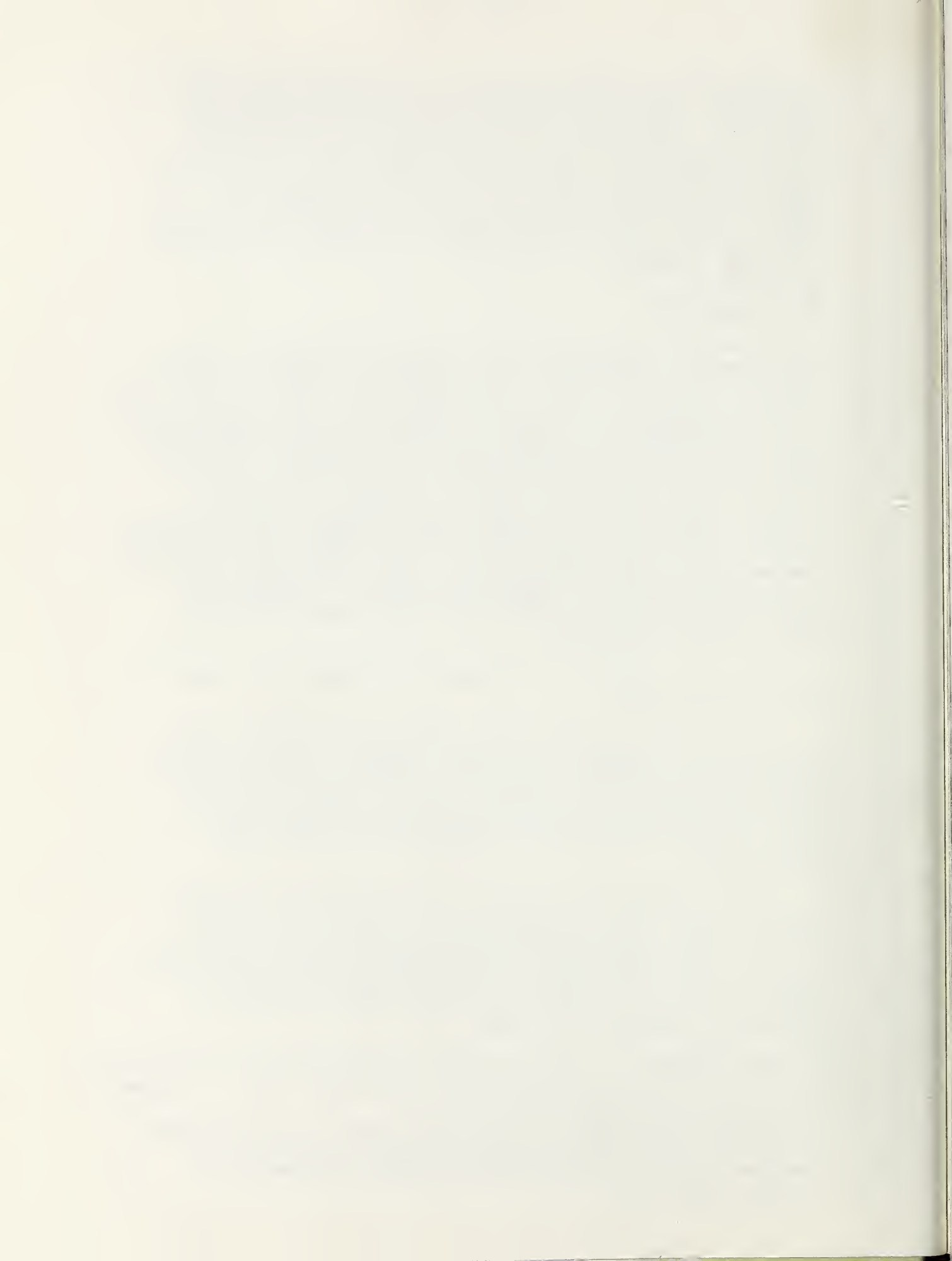
3) For ease of computation, yearly replenishment of the de-
cayed portion of cobalt-60 is assumed and treated as a yearly
expense. Operators of irradiators with small loadings are more
likely to purchase enough cobalt-60 to allow several years of
maximum operation rather than incur the high transportation charges
of annual replenishment. Therefore, costs may be slightly over-
stated for small irradiators with low cobalt loadings.

4) All irradiators were assumed to be free standing
facilities located on 1.2 hectares of land 3/. In addition to
the irradiation cell and labyrinth, building space is required
for offices, the control panel area, a laboratory to conduct
tests to verify the dose received, a room for power sources to
run the machinery, and product loading and unloading areas.
Storage space is also needed to hold product before and after
irradiation. The refrigerated warehouse space needed was based
on storing a four-day supply of each irradiator's processing
capacity. The assumed sizes and costs for these rooms are listed
in Appendix A.

5) Boxes of product were assumed to be hand stacked in an
arrangement compatible with the design of the conveyor system
continually moving product through the irradiator cell. Overdose
ratios associated with treating pallet loads of products are
larger than those experienced when handling smaller loads [3].
For applications where the minimum to maximum dosage ratio is
large and overdosing is not a problem, foods may be able to be
handled in pallet loads. This arrangement would reduce costs
for material handling. To be on the conservative side, however,
it was assumed that pallet-size loads could not be treated.
The number of product handlers needed to load and unload the
conveyor are listed in Appendix B. Labor is also needed for
handling product when shipments arrive at and leave the facility
(see Appendix C).

6) Finally, several general assumptions were made to adapt
the earlier U.S. analysis to input prices more typical of a
developing country:

° Construction costs for the irradiator cell and other build-
ings were assumed to be equal to U.S. buildings of comparable size.

° Machinery costs were increased by 20 percent to reflect
higher transportation and installation costs and less local price
competition.

_____
3/ An irradiator could be built as part of a packing house or
processing facility, in which case several cost components could
be shared with the processing facility (see discussion in [2]).

° Costs for maintenance, supplies, and utilities were raised from 1.5 and 2 percent of facility costs to 3 and 4 percent to reflect the need for more spare parts and higher utility costs expected in developing countries.

° Based on a comparison of international labor costs compiled by the U.S. Bureau of Labor Statistics, labor costs for food irradiation employees are expected to be lower in developing countries than in the United States [4]. Therefore, salaries and wages were reduced to 25 percent of U.S. levels for skilled labor and to 10 percent of U.S. wages for the unskilled product handlers for the base case scenario 4/.

° Products were assumed to be moved in and out of storage in pallet loads by forklifts. Because of relatively low labor costs in developing countries, palletizing machines that reduce human labor were not used.

The full set of input prices underlying this analysis are listed in Appendix A. If the relative prices of production inputs differ dramatically from those used here, an irradiator operator is likely to select a different combination of inputs to achieve least cost output. This would affect the scale economies.

Annualizing Fixed and Variable Costs

The costs of building and operating an irradiator of a given hourly capacity are divided into fixed and variable costs. Together they constitute the total cost of operation for a given level of output. Fixed costs remain unchanged as output is altered. For example, once the biological shielding and machinery are built to accommodate a particular processing capacity, the cost of using these inputs will not change if output is reduced. In contrast, the cost of inputs such as utilities and hourly labor do vary with the use of the irradiator and the corresponding output. Table 1 shows the division between fixed and variable costs for irradiators providing a dose of 0.25 kGy under the base case scenario. Hourly labor, supplies, utilities, and maintenance that depends on how much the facility is used are considered variable cost items.

Fixed and variable costs were expressed on an annual basis so that total costs could be divided by annual output to derive unit costs. Recurring expenses like utilities, salaries, and cobalt-60 replenishment were already expressed on a yearly basis. A capital recovery factor was used to estimate the levelized annual cost of the biological shielding, buildings, machinery, and the initial cobalt-60. This factor computes the amount needed to recover the original investment (purchase price) plus the opportunity cost of the money spent to buy the asset

---

4/ The base case scenario assumes a three-shift operation, 250 processing days a year, wage levels of 25 and 10 percent of U.S. levels, and a 10 percent opportunity cost for capital funds.

over its useful life. The formula is defined in Appendix A.
Crucial variables in the capital recovery formula are the interest
rate, or opportunity cost of money, and the assumed useful life
of the asset. For the base case scenario, the interest rate
was 10 percent. The useful lives for the capital assets were
assumed to be 25 years for buildings and biological shielding,
10 years for machinery, and 15 years for the initial cobalt-60
loading. The annual fixed and variable costs for each irradiator
operated three shifts per day are listed in table 2.

Resulting Economies of Scale

Economies of scale are reflected in the shape of the long-
run average cost curve as scale increases. The steeper the
curve, the greater the economies of scale. The long-run cost
curve shows the minimum average cost of producing each output
level when all inputs are variable and a firm is free to choose
any plant size. One method that economists use to approximate
the long-run cost curve is to examine a series of short-run
average cost curves for individual plants of different sizes
and select minimum unit costs for each output level.

Short-run cost curves for each size irradiator are estimated
by computing costs when the irradiator is operated for one, two,
and three 8-hour shifts per day. Variable costs are estimated
for each shift. Fixed costs are based on a predetermined processing
capacity (throughput per hour) and remain constant as fewer
shifts are operated and annual output drops. Figures 1 through
4 show the cost curves for the model irradiators in this analysis.

Table 3 lists irradiation treatment costs per kilogram for
the base case scenario. Unit costs for the volumes analyzed
range from 4.0 and 6.1 cents per kilogram to 1.2 and 3.3 cents
per kilogram, depending on the radiation dose applied 5/.
Increasing the dosage from 0.1 to 2.5 kGy raises average treatment
costs by about 2 cents per kilogram for each size. All four
irradiators exhibit economies of scale, as demonstrated by
their decreasing unit costs as processing capacity increases.
This means that, considering only the treatment cost, larger
irradiators would be able to treat products at a lower unit
cost than small irradiators. However, in all cases the scale
economies become less pronounced as size increases. Potential
scale economies become less important at annual volumes greater
than 31.5 million kilograms (about 16,000 metric tons). For
example, unit costs for the two largest irradiators, treating
9,000 and 12,000 kilograms an hour, respectively, differ by
only 0.1 cent per kilogram regardless of dose. Unit costs for
irradiators treating 6,000 and 9,000 kilograms per hour differed
by only 0.2 to 0.3 cent per kilogram.

Economies of scale result from production inputs expanding
less than proportionally with increases in plant capacity. To

_____
5/ All costs in this paper are in U.S. currency.

determine the source of the economies, one examines how the major components change with size. Cobalt-60, building and shielding, machinery, and labor accounted for about 70 percent of unit costs in these scenarios. For a cobalt-60 irradiator, the most important sources of production economies are labor, buildings and shielding, and machinery.

Certain employees--plant manager, maintenance, and clerical personnel--are needed regardless of the volume moving through the irradiator. Costs for other employees--radiation safety officer/quality control person, plant operators, and documentation clerks--will vary with the number of shifts operated, but not with the volume of the irradiator 6/. Thus, spreading their salaries over larger outputs lowers average labor costs. When salaried employees are a major cost item, such as in the irradiators treating 1,500 and 3,000 kilograms per hour, large scale economies occur with relatively small increases in size. Conversely, the number of material handlers needed does vary with irradiator size, so as their numbers grow and they become a more important component of labor costs, scale economies attributed to labor costs are moderated. This moderates overall scale economies and lessens the decline in unit costs for irradiators in the large volume range. For each dose in table 3, unit costs drop by 1.7 cents between the two smallest irradiators, compared with a 0.1-cent drop between the two largest irradiators.

Buildings, shielding, and machinery costs are likely to follow the general construction relationship where productive capacity increases faster than cost, although at a declining rate as scale increases [5]. As a result, as productive capacity in table 1 increases 8-fold, the annual charge for these capital items rises less than 3-fold. The magnitude of the scale economies, however, are greater for irradiators in the small volume range.

Cobalt-60 is an important cost item, especially for large capacity irradiators. However, cobalt-60 is not a source of production economies because cobalt needs are directly related to hourly throughput. Only minor economies could be realized through cobalt-60 suppliers offering volume discounts. As plant capacity increases for each dose level in table 3, cobalt becomes a larger portion of total costs and fewer scale economies are possible. This is illustrated by the declining rate of reduction in unit costs for all applications.

Raising the dose of radiation applied to the food also causes cobalt-60 to become a greater portion of total costs. Therefore, the irradiators applying a dose of 2.5 kGy demonstrate fewer scale economies--unit costs for the 2.5 kGy application in table 3 drop by only 46 percent over the size range compared to a 70-percent drop for the 0.1 kGy application.

6/ Salaries were not assumed to change as irradiator size increased because of the relatively small work force (all sizes employed less than 50 people) and the fact that the skill levels of the employees do not change much as size increases.

Sensitivity to Labor and Capital Costs

Labor and capital costs vary among countries and individual situations. For this reason, it is important to test the sensitivity of long-run scale economies to changes in these two factors.

Table 4 lists per unit irradiation treatment costs for the four model irradiators for three sets of labor costs. Scenario B represents base labor costs. Labor costs in scenario A are assumed to be 50 percent of levels in the base case, while labor costs in scenario C are assumed to be twice those of the base case. As shown in the last column of table 4, the decline in unit costs between the smallest and largest irradiators for each dose level increases as labor costs rise, i.e., as labor costs increase, the economies of scale increase. This is because the scale economies inherent in labor cost are greater than the scale economies inherent in annual capital charges (those costs affected by interest rates) and in other cost items.

The scale economies inherent in the major cost categories—labor, annual capital charges, and other costs—can be determined by the ratio of largest facility to smallest facility for each category. As can be seen in table 5, labor costs expand by a factor of only 1.75 as output expands by a factor of 8.00, while annual capital charges expand by a factor of 2.71 and other cost items expand by a factor of 3.03. Since all cost items expand less than proportionally with output, total costs expand by only a factor of 2.53, and long-run scale economies exist.

Any change in the distribution of total costs among the cost items, however, will change the overall scale economies. If labor costs double for all plant sizes while other costs and the mix of inputs remain constant, labor cost will constitute a greater portion of total cost 7/. Since this cost change will not affect the relative scale economies inherent in labor (labor costs will still increase by a factor of 1.75 if production increases by a factor of 8.00), increasing labor's share of total cost will increase the overall scale economies. This is demonstrated in table 6, which shows that doubling labor costs results in greater long-run economies of scale. When production increases 8-fold, total cost increases by a factor of 2.35 as compared to 2.53 in table 5. Therefore, countries with higher labor costs could expect more pronounced economies of scale than countries with lower labor costs, holding the input mix and other input prices constant.

7/ The nature of radiation processing allows very little substitution of capital for labor. In a continuous operating irradiator the one function where this substitution could occur is by palletizing machinery replacing some of the product handlers. However, with the wages and machinery costs used in this analysis, substitution of capital (machinery) for labor would cause unit costs to rise.

On the other hand, larger annual capital charges <u>reduce</u> the magnitude of long-run economies of scale since the scale economies inherent in annual capital charges are smaller than the overall scale economies realized in the base case. If annual capital costs double for all plant sizes while other costs remain constant, annual capital charges will constitute a larger share of total cost. Since this cost change will not affect the relative scale economies inherent in capital, increasing capital's share of total cost will reduce the overall scale economies. This is demonstrated in table 7, which shows that doubling capital charges results in smaller long-run economies of scale. As production increases by a factor of 8.00, total costs increase by a factor of 2.58 as compared to 2.53 in table 5. Thus, countries with larger capital costs because of higher construction costs, import fees on machinery, or high interest rates could expect less pronounced economies of scale than countries with lower capital charges, all other factors held constant.

These effects of changing labor costs and capital charges on long-run economies of scale are true for all doses. Lower labor costs and higher capital charges decrease economies of scale. For these reasons, economies of scale for cobalt-60 irradiators are expected to be less dramatic for developing countries than than for developed countries.

Short-Run Cost Curves

Irradiators are likely to operate at less than capacity during part of the year if irradiation is used to treat seasonal products such as fruits and vegetables. Even commodities grown year round often have definite seasonal harvest patterns. To accommodate seasonal peaks requiring large hourly capacity, food irradiators would have excess capacity during off periods. Animal products are subject to less seasonal fluctuations, but cyclical swings over time could adversely affect use of irradiator capacity.

The short-run cost curves in figures 1 through 4 illustrate the cost penalties of operating a plant at less than full capacity, i.e. less than three shifts or less days per year. Table 8 lists the unit costs for throughputs equivalent to one, two, and three shift operating schedules. Several observations can be made about the short-run costs where usage, not plant size, changes.

° For all dose levels, unit costs climb as plants are run less than full capacity because there is less output over which to spread fixed costs.

° The penalty for operating at less than full capacity is greater for small irradiators than larger ones because fixed costs become a greater proportion of total costs more rapidly in small plants. This relationship is illustrated in figure 5. If production in the second smallest irradiator is cut by 5.25 million kilograms, from 15.75 to 10.5 million kilograms, unit costs rise by 1.4 cents per kilogram. If production in the second largest irradiator is

also cut by 5.25 million kilograms, from 47.25 to 42 million kilograms, unit costs rise by only 0.3 cent per kilogram.

° Irradiators applying higher doses incur greater cost penalties for operating less than three shifts compared to low-dose irradiators of the same size. For example, with the 6,000 kilogram per hour irradiator applying a 0.1 kGy dose, operating one shift rather than three results in 50 percent greater unit costs. For the same size irradiator applying a 2.5 kGy dose, unit costs for a one shift operation are 55 percent greater. In absolute terms, the cost penalty is 1.5 cents per kilogram for the 0.1 kGy dose and 4.5 cents per kilogram for the 2.5 kGy dose. This occurs because fixed costs, of which cobalt is a component, are larger for higher-dose irradiators.

° For small irradiators with low cobalt loadings, such as the 1,500 and 3,000 kilogram per hour irradiators applying doses of 0.1 and 0.25 kGy, lower unit costs can be realized by running a larger plant at less than full capacity than running a small plant at full capacity because of the savings in var- iable labor costs and supplies and utilities (see cost curves in figures 1 and 2). However, at higher annual volumes or higher dose levels, savings in variable costs do not outweigh increasing fixed costs. In these cases, unit costs would be greater when an irradiator is run at less than capacity compared with a smaller one operated at full capacity. The short-run cost curves for the irradiators applying a dose of 2.5 kGy, shown in figure 4, illustrate the point clearly. Running a plant designed to treat 63 million kilograms per year only one shift results in an average unit cost of 7.5 cents per kilogram, compared to operating a smaller plant at its three shift capacity where the unit cost is expected to be around 4 cents per kilogram.

Locating an irradiator in agricultural production areas with sequential harvest times for different irradiation-compatible commodities or irradiating non-agricultural items during off seasons would lessen the problem of not operating the irradiator at full capacity.

Conclusions and Other Considerations

This paper presented estimates of average unit costs for five sizes of cobalt-60 irradiators treating food products with one of four dose levels of radiation. Irradiation technology demonstrates economies of scale with unit costs declining as the irradiator's size increases. These economies of scale are very pronounced for small irradiators, which means that individual agricultural firms with volumes less than 15 million kilograms per year will not be able to achieve the lower unit costs possible with high throughputs. However, potential scale economies in this analysis generally become less important at volumes greater than 31.5 million kilograms per year.

Food irradiation economies of scale are expected to be somewhat less dramatic for developing countries than for developed countries because of lower labor costs. At the same time, food irradiation is a capital intensive technology where human labor can not substitute for the thick shielding or the conveyor system needed to move products past the radiation source. Thus, the actual relationship between facility size and construction costs and machinery in developing countries will also have an important influence on the scale economies. Given a production input mix similar to that used in this analysis, countries with high construction costs or high interest rates can expect less dramatic scale economies.

An analysis of plant economies of scale for irradiation treatment is one factor to be considered when selecting the appropriate sized irradiator. However, transportation costs and disruptions to current marketing procedures should also be considered. The unit costs reported in this paper are for the radiation treatment alone. For free standing facilities that combine throughputs from several producers, the costs of shipping the commodity to the irradiator are an added cost. As free standing irradiators increase in size, they will have to draw on larger geographic areas for their throughput. The transportation costs of shipping the commodities to the larger irradiator may outweigh any gains in plant scale economies. This may bring the total cost of using a small irradiator more closely in line with that of a large irradiator.

A non-production cost of interest to potential users is the cost of research and development for determining the optimal dose of radiation for a particular food and application. Other costs include the cost of training personnel to operate an irradiation facility and any public funds needed to regulate the technology and insure its safety for workers in the facility, consumers, and the environment.

Acknowledgements

REFERENCES

[1] LAPIDOT, M., "Introducing irradiated agricultural products
     on a large scale--a test study in a developing country,"
     Factors Influencing the Economical Application of Food
     Irradiation (Panel Proc. Series, Vienna, 1971), IAEA,
     Vienna (1973), 67.

[2] MORRISON, R.M., "Economies of Scale in Single Purpose Food
     Irradiators", IAEA-SM-271-63 paper presented at the IAEA/FAO
     International Symposium on Food Irradiation Processing,
     Washington, D.C., March 4-8, 1985.

[3] DIETZ, G.R., "The Role and Availability of Contrat Gamma
     Sterilization Facilities," paper presented at the Atomic
     Energy of Canada Limited's Third Gamma Processing Seminar,
     Ottawa, Canada, June 7, 1983.

[4] U.S. DEPARTMENT OF LABOR, Bureau of Labor Statistics, Office
     of Productivity and Technology, "Hourly Compensation Costs
     for Production Workers in Textile Mill Products Manufacturing,
     24 Countries, 1975-1982," unpublished data, April 1984.

[5] McGEE, J.S., "Efficiency and Economies of Size," Industrial
     Concentration: The New Learning, (GOLDSCHMID, H.J., MANN, H.M.,
     WESTON, J.F., Eds) Little, Brown and Co., Boston (1974), 58.

Table 1. Capital Investment and Fixed and Variable Costs for Irradiators Applying
Dose of 0.25 kGy 1/

Budget items	Processing Capacity--Hourly Throughput in kg.				
	1500	3000	6000	9000	12000
FIXED COSTS			U.S. dollars		
Initial loading					
curies	31600	63100	126200	186500	252500
delivery & rigging	15800	31600	63100	93300	126300
total (rounded)	47000	95000	189000	280000	379000
Biological shielding	290000	305000	330000	350000	400000
Irradiator machinery	300000	324000	414000	600000	750000
Auxilary systems	24000	36000	36000	36000	42000
Control room and dosimetry lab	17000	17000	17000	17000	17000
Fork lifts	36000	36000	36000	36000	72000
Refrigerated warehouse	75000	150000	300000	450000	600000
Additional rooms	59000	59000	63000	76000	84000
TOTAL FACILITY COST	848000	1022000	1385000	1845000	2344000
Design and engineering	85000	102000	139000	185000	234000
Fixed maintenance	9000	11000	15000	19000	25000
Land	15000	15000	15000	15000	15000
Insurance and taxes	0	0	0	0	0
Labor:					
plant manager	11400	11400	11400	11400	11400
maintenance	6500	6500	6500	6500	6500
clerical ·	4600	4600	4600	4600	4600
total (rounded)	23000	23000	23000	23000	23000
Working capital	45000	51000	70000	85000	101000
TOTAL FIXED COSTS	1025000	1224000	1647000	2172000	2742000

(con't.)

Table 1. Continued

Processing Capacity--Hourly Throughput in kg.

VARIABLE COSTS		1500		3000		6000		9000		12000
Labor										
RSO/QC		29400		29400		29400		29400		29400
shift supervisor		0		0		26400		26400		26400
plant operator		17700		17700		17700		17700		17700
documentation		13800		13800		13800		13800		13800
product handlers 2/	6	12000	10	20000	16	32000	23	46000	29	58000
Supplies		34000		41000		55000		74000		94000
Utilities		34000		41000		55000		74000		94000
Variable maintenance		17000		20000		27000		36000		46000
TOTAL VARIABLE COSTS		157900		182900		256300		317300		379300
ANNUALIZED FIXED COSTS										
Source										
initial loading		6179		12490		24849		36813		49829
replenishment		5300		10500		21000		31100		42100
Building and shielding		57948		69736		93533		118761		147074
Machinery		58598		64447		79094		109365		140612
Land		1500		1500		1500		1500		1500
Working capital		4500		5100		7000		8500		10100
Fixed maintenance		9000		11000		15000		19000		25000
Insurance and taxes		0		0		0		0		0
Salaried employees		23000		23000		23000		23000		23000
TOTAL FIXED (rounded)		166000		198000		265000		348000		439000
UNIT COST $/kg.		0.0411		0.0242		0.0165		0.0141		0.013

1/ The irradiation treatment costs in this table are based on a 3-shift operation, with a 10 percent opportunity cost for capital funds. Labor costs are assumed to be 25 percent of U.S. labor costs for skilled labor and 10 percent of U.S. costs for unskilled product handlers. Other assumptions and input prices are listed in Appendix A.

2/ The numbers in parentheses are the number of product handlers needed per day for a 3-shift operation.

Table 2. Summary of Investment and Annual Costs for Selected Cobalt-60 Irradiators 1/

Dose Level and Annual Throughput in Millions of kg.	Cobalt-60 Loading 2/	Initial Investment 3/	Annualized Fixed Costs 4/	Annual Variable Costs 5/	Annual Total Cost
	1,000 curies	$1,000,000	$1,000	$1,000	$1,000
0.1 kGy					
7.875	12.6	1.0	159	155	314
15.75	25.2	1.1	182	178	360
31.5	50.5	1.5	234	246	480
47.25	75.7	1.9	304	300	604
63.0	101.0	2.4	378	356	734
0.25 kGy					
7.875	31.6	1.0	166	158	324
15.75	63.1	1.2	198	183	381
31.5	126.2	1.6	265	256	521
47.25	186.5	2.1	348	317	665
63.0	252.5	2.7	439	379	818
0.5 kGy					
7.875	63.1	1.0	178	162	340
15.75	126.2	1.3	223	193	416
31.5	252.5	1.8	316	276	592
47.25	378.7	2.5	425	345	770
63.0	504.9	3.1	544	419	963
2.5 kGy					
7.875	315.6	1.5	279	200	479
15.75	631.1	2.2	429	270	699
31.5	1,262.3	3.6	724	430	1,154
47.25	1,893.4	5.0	1,036	573	1,609
63.0	2,524.5	6.6	1,352	720	2,072

1/ Costs in this table are expressed in U.S. dollars and based on 3-shift operation, with a 10 percent opportunity cost for capital funds. Labor costs are assumed to be 25 percent of U.S. labor costs for skilled labor and 10 percent of U.S. costs for unskilled product handlers. Other assumptions and input prices are listed in Appendix A.
2/ Cobalt-60 loadings were determined using the formula described in Appendix A.
3/ Investment items include: cobalt-60, biological shielding and other building space, irradiator machinery and auxilary systems, product handling equipment, refrigerated warehouse space, design and engineering, land, and working capital.
4/ Includes the annualized costs for investment items and annual costs for cobalt-60 replenishment, fixed maintenance, and fixed labor.
5/ Includes wages of variable labor and product handlers, supplies, utilities, and variable maintenance.

Table 3.   Irradiation Unit Costs 1/

Dose	Processing Capacity--Hourly throughput in kg.				
	1,500	3,000	6,000	9,000	12,000
	Annual throughput in millions of kg. 2/				
	7.875	15.75	31.5	47.25	63.0
kGy	U.S. cents per kg.				
0.1	4.0	2.3	1.5	1.3	1.2
0.25	4.1	2.4	1.7	1.4	1.3
0.5	4.3	2.6	1.9	1.6	1.5
2.5	6.1	4.4	3.7	3.4	3.3

1/ The irradiation treatment costs in this table are based on
a 3-shift operation, with a 10 percent opportunity cost for
capital funds. Labor costs are assumed to be 25 percent
of U.S. labor costs for skilled labor and 10 percent of
U.S. costs for unskilled product handlers. Other assumptions
and input prices are listed in Appendix A.

2/ Annual throughputs are based on treating foods 21 hours a
day, 250 days per year.

Table 4. Irradiation Unit Costs with Varying Labor Costs 1/

ose Labor costs 3/	Processing Capacity--Hourly throughput in kg.					Decline between smallest and largest	
	1,500 2/	3,000 2/	6,000	9,000	12,000	cents	percent
	U.S. cents per kg.						
.1 kGy							
A	3.4	1.9	1.3	1.1	1.0	2.4	69.3
B	4.0	2.3	1.5	1.3	1.2	2.8	70.7
C	5.2	3.0	2.0	1.6	1.4	3.8	72.4
.25 kGy							
A	3.5	2.1	1.4	1.2	1.2	2.3	66.6
B	4.1	2.4	1.7	1.4	1.3	2.8	68.4
C	5.3	3.1	2.1	1.7	1.6	3.7	70.5
.5 kGy							
A	3.7	2.3	1.7	1.5	1.4	2.3	62.3
B	4.3	2.6	1.9	1.6	1.5	2.8	64.6
C	5.6	3.3	2.3	2.0	1.8	3.8	67.6
.5 kGy							
A	5.5	4.1	3.4	3.2	3.2	2.3	42.2
B	6.1	4.4	3.7	3.4	3.3	2.8	45.9
C	7.3	5.1	4.1	3.7	3.6	3.7	51.2

1/ The irradiation treatment costs in this table are based on a 3-shift operation, with a 10 percent opportunity cost for capital funds. Other assumptions and input prices are listed in Appendix A.
2/ No shift supervisor needed because of small number of employees.
3/ Labor costs were reduced to the indicated percentage of U.S. labor levels. The first percentage is the adjustment made to skilled labor, and the second percentage is the adjustment made to unskilled product handlers. The labor costs used are as follows:

	Scenario A 12.5%/5%	Scenario B 25%/10%	Scenario C 50%/20%
Fixed (per year)			
plant manager	$5,700	$11,400	$22,800
maintenance	3,300	6,500	13,000
clerical	2,300	4,600	9,100
Variable (per 8 hr. shift per year)			
radiation safety officer/ quality control	4,900	9,800	19,500
shift supervisor	4,400	8,800	17,500
plant operator	2,900	5,900	11,700
documentation clerk	2,300	4,600	9,100
product handler	1,000	2,000	4,000

Table 5. Scale Economies Inherent in Selected Cost Items
(0.25 kGy Irradiator)

	Smallest Facility	Largest Facility	Ratio of Largest to Smallest Facility
Labor costs	$95,900	$168,300	1.75
Annual capital charges	$128,700	$349,100	2.71
Other cost items	$99,300	$300,900	3.03
Total cost	$323,900	$818,300	2.53
Annual production volume (kg)	7,875,000	63,000,000	8.00

Table 6. Scale Economies If Labor Costs Are Doubled
(0.25 kGy Irradiator)

	Smallest Facility	Largest Facility	Ratio of Largest to Smallest Facility
Labor costs	$191,800	$336,600	1.75
Annual capital charges	$128,700	$349,100	2.71
Other cost items	$99,300	$300,900	3.03
Total cost	$419,800	$986,600	2.35
Annual production volume (kg)	7,875,000	63,000,000	8.00

Table 7. Scale Economies If Capital Costs Are Doubled
(0.25 kGy Irradiator)

	Smallest Facility	Largest Facility	Ratio of Largest to Smallest Facility
Labor costs	$95,900	$168,300	1.75
Annual capital charges	$257,400	$698,200	2.71
Other cost items	$99,300	$300,900	3.03
Total cost	$452,600	$1,167,400	2.58
Annual production volume (kg)	7,875,000	63,000,000	8.00

Table 8.   Irradiation Unit Costs for Three Levels of Operation 1/

Dose Throughput Level 2/	Processing Capacity--Hourly Throughput in kg.				
	1,500	3,000	6,000	9,000	12,000
	U.S. cents per kg.				
0.1 kGy					
1 shift	7.9	4.6	3.0	2.5	2.3
2 shifts	5.0	2.9	1.9	1.6	1.5
3 shifts	4.0	2.3	1.5	1.3	1.2
0.25 kGy					
1 shift	8.2	4.9	3.3	2.9	2.7
2 shifts	5.2	3.0	2.1	1.8	1.6
3 shifts	4.1	2.4	1.7	1.4	1.3
0.5 kGy					
1 shift	8.7	5.4	3.9	3.4	3.2
2 shifts	5.4	3.3	2.4	2.1	2.0
3 shifts	4.3	2.6	1.9	1.6	1.5
2.5 kGy					
1 shift	13.0	9.8	8.2	7.7	7.5
2 shifts	7.8	5.8	4.8	4.5	4.4
3 shifts	6.1	4.4	3.7	3.4	3.3

1/ The irradiation treatment costs in this table are based on a 10 percent opportunity cost for capital funds, and labor costs are assumed to be 25 and 10 percent of U.S. labor costs for skilled and unskilled labor, respectively. Other assumptions and input prices are listed in Appendix A.

2/ Annual throughput levels equivalent to one, two, and three shift operating schedules for each irradiator size are as follows:

	1,500	3,000	6,000	9,000	12,000
	Millions of kg. per year				
1 shift	2.625	5.25	10.5	15.75	21.0
2 shifts	5.25	10.5	21.0	31.5	42.0
3 shifts	7.875	15.75	31.5	47.25	63.0

IRRADIATION COSTS   0.1 KGY
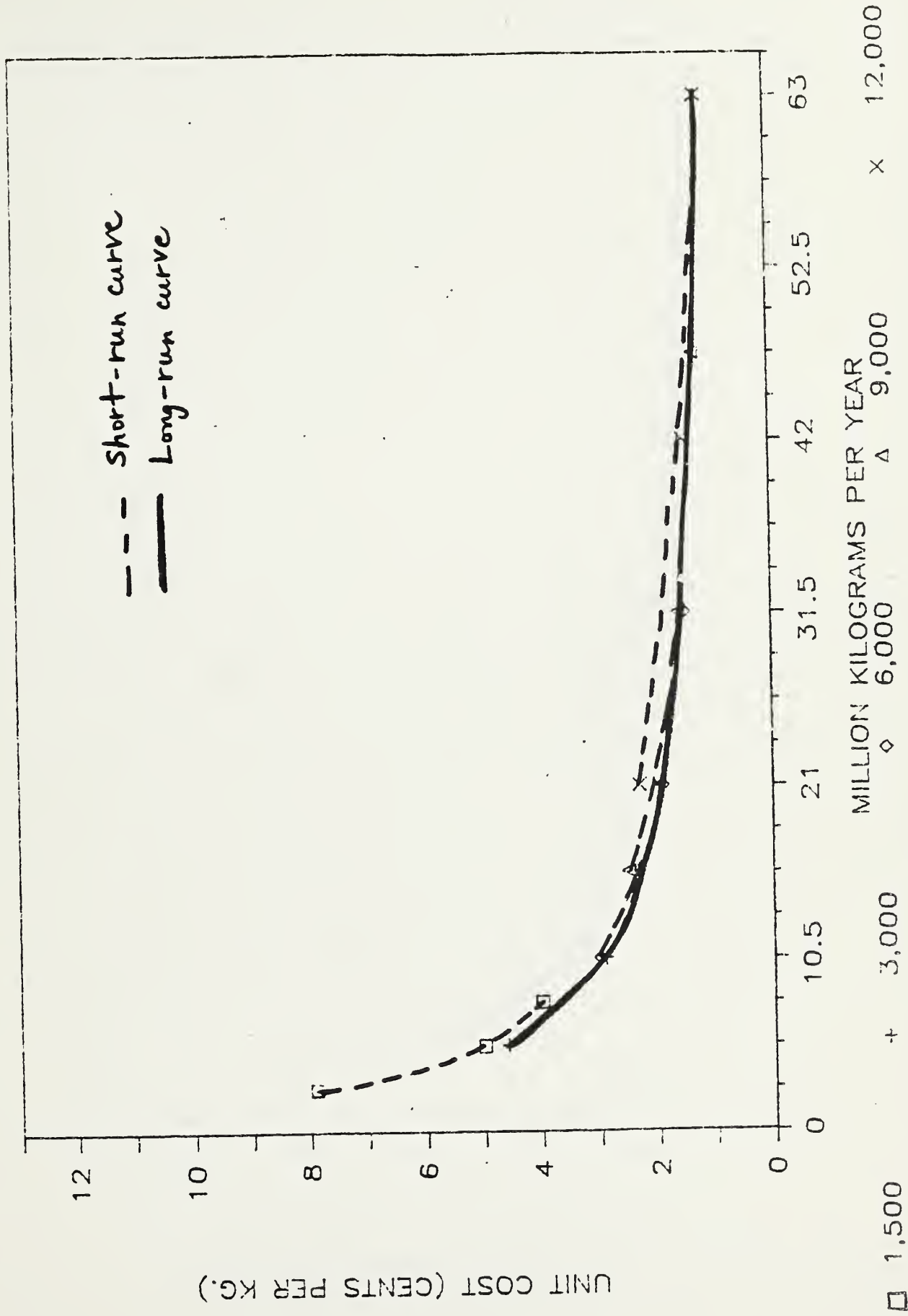
Figure 1,

IRRADIATION COSTS 0.5 KGY

UNIT COST (CENTS PER KGY.)

MILLION KILOGRAMS PER YEAR

Short-run curve
Long-run curve

□ 1,500   + 3,000   ◇ 6,000   △ 9,000   × 12,000
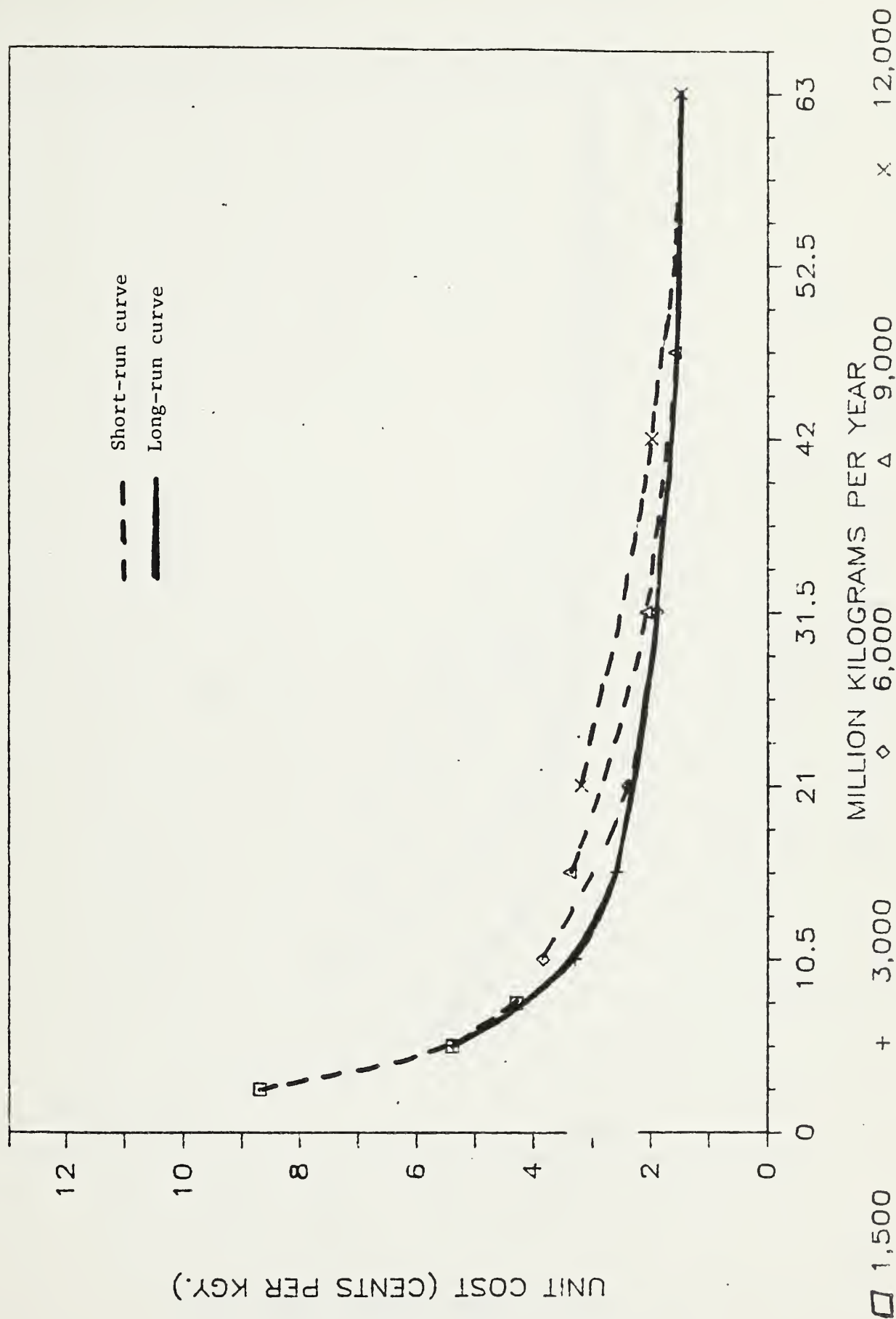
Figure 3.

IRRADIATION COSTS 2.5 KGY
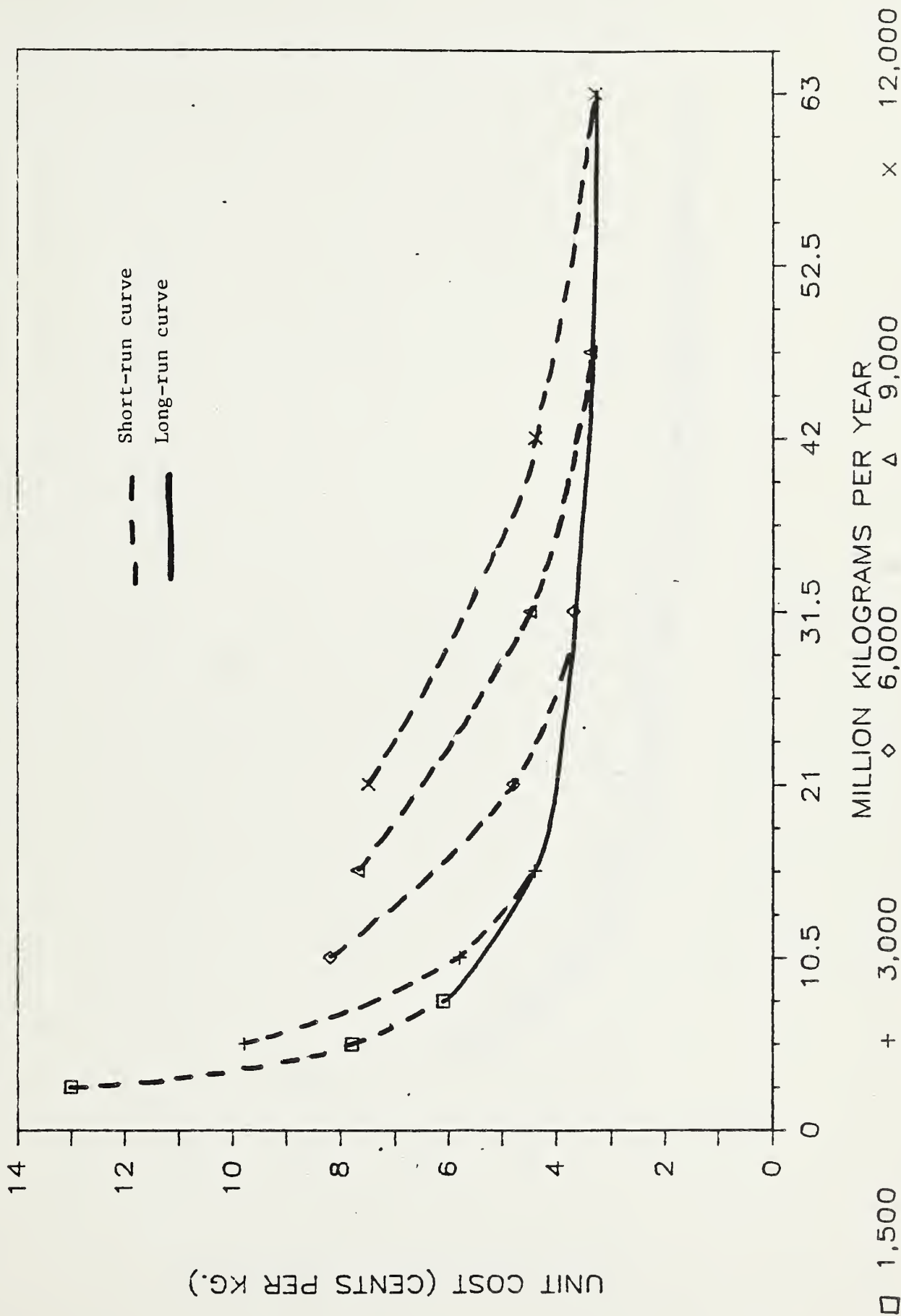
Figure 4.

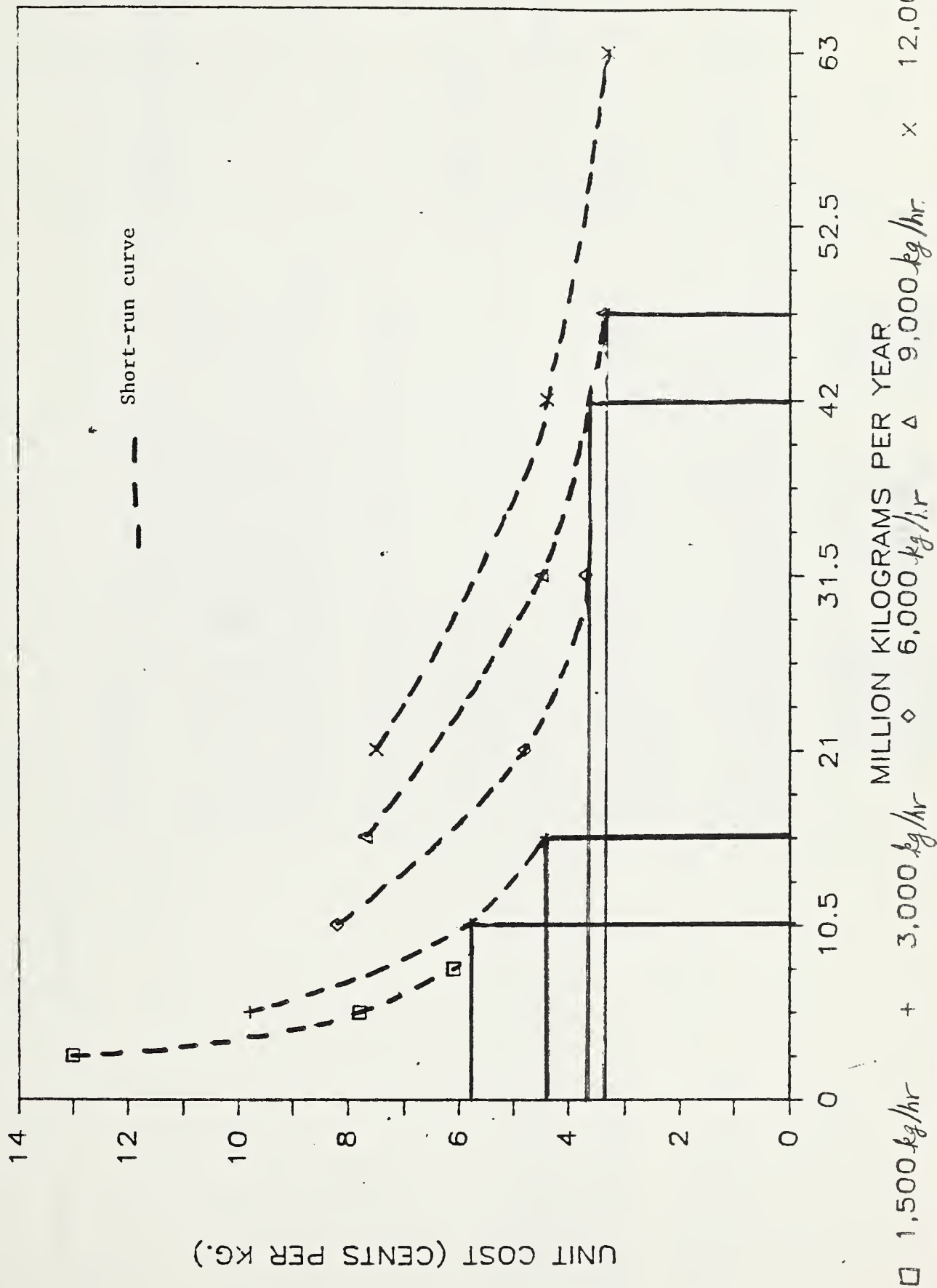# IRRADIATION COSTS 0.25 KGY
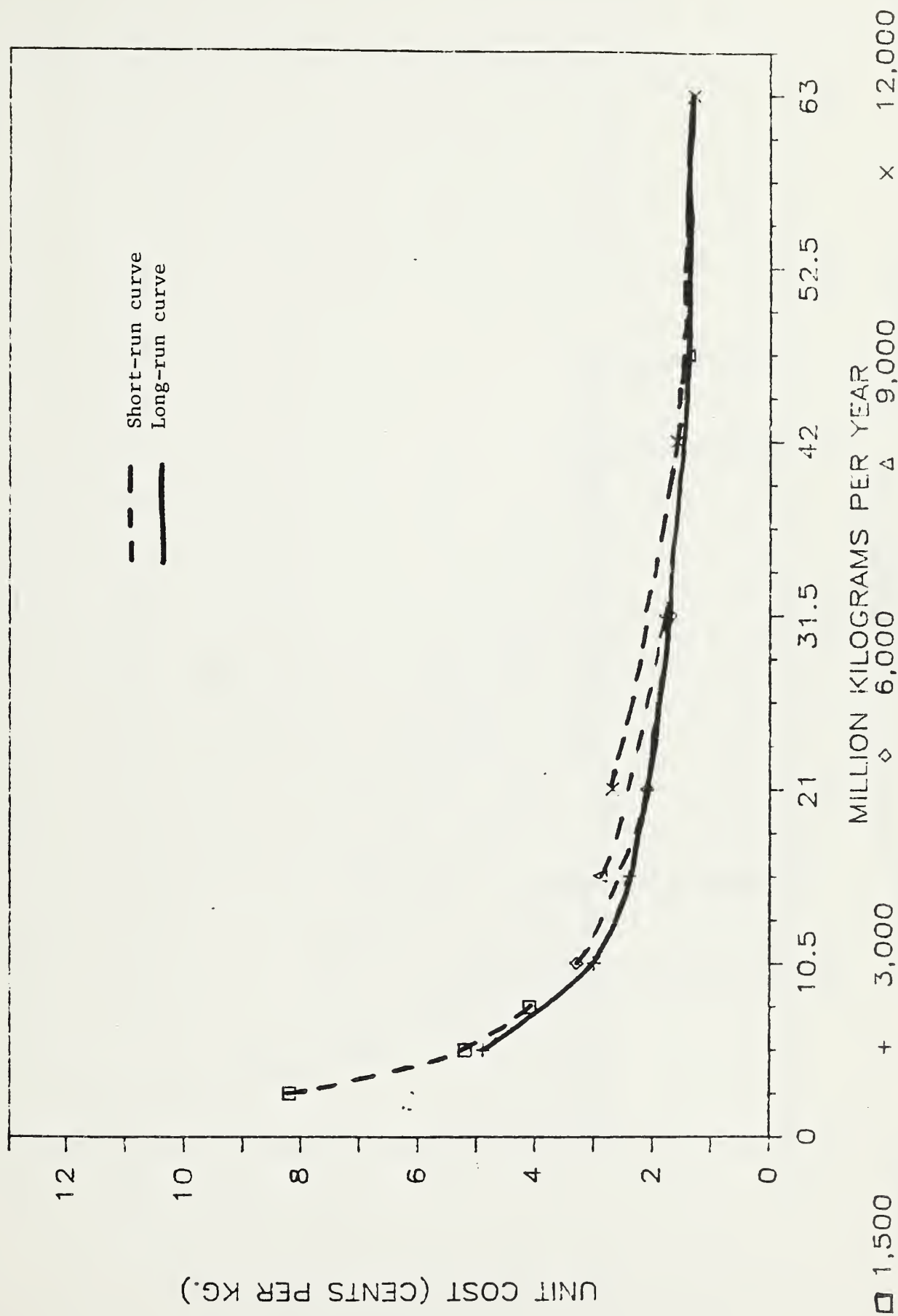
Figure 2.

IRRADIATION COSTS 2.5 KGY

Short-run curve

- - - Short-run curve

UNIT COST (CENTS PER KG.)

14 12 10 8 6 4 2 0

0   10.5   21   31.5   42   52.5   63

MILLION KILOGRAMS PER YEAR

□ 1,500 kg/hr   + 3,000 kg/hr   ◇ 6,000 kg/hr   △ 9,000 kg/hr   × 12,000 kg/hr

Figure 5

APPENDIX A.

Budget Item	Formulae and Assumptions	Source
FIXED COSTS (All costs expressed in U.S. dollars.)		
Integrated and Free Standing Facilities		
Curie load	# of curies = $\dfrac{85 \times \text{throughput in lbs. per hr.} \times \text{dose (in megarads)}}{\text{net utilization efficiency}}$ Net utilization efficiency was assumed to be 25% for all irradiators for this analysis. Actual net utilization efficiency depends on the design of the irradiator which must consider product density and dose uniformity needs. Net utilization efficiency is expressed as a fraction of 1, where 1 = 100% ^{60}Co utilization efficiency. An additional 12.5% for yearly decay was added to initial loading. Price of ^{60}Co assumed to be $1.00 per curie for this analysis.	Jarrett, 1983, p. 150-51. Formula modified by author. Atomic Energy of Canada, Ltd.
Delivery and loading of ^{60}Co	$0.5 per curie	Author's assumption.
Source replenishment	12.5% required each year (delivery and loading costs same as above) to maintain previous year's throughput.	Deitch, et. al., 1972, p. 65.
Biological Shielding	Costs for concrete cell and labrinth and water-filled pool were estimated based on ft^3, where kg/hr were divided by 9.1 kg/ft^3 to reflect an average weight to volume relationship for boxed product. 1,500 kg/hr = 165 ft^3/hr $290,000 3,000 kg/hr = 330 ft^3/hr $305,000 6,000 kg/hr = 660 ft^3/hr $330,000 9,000 kg/hr = 990 ft^3/hr $350,000 12,000 kg/hr = 1,320 ft^3/hr $400,000	Morrison, 1985, Appendix A (modified).

Budget Item	Formulae and Assumptions	Source
Irradiator Machinery: °source hoist and plaque } A °control panel °mechanical interlocks °conveyor } B °carriers	Costs were estimated as follows: A B 165 ft³/hr $180,000 + $120,000 330 ft³/hr $180,000 + $144,000 660 ft³/hr $210,000 + $204,000 990 ft³/hr $240,000 + $360,000 1,320 ft³/hr $270,000 + $480,000	Morrison, 1985, Appendix A (modified and costs increased by 20 percent to reflect transportation charges and less local competition).
Auxilary Systems: °deionizer °chiller °air handling	Costs were estimated as follows: 165 ft³/hr $48,000 330 ft³/hr $60,000 660 ft³/hr $60,000 990 ft³/hr $60,000 1,320 ft³/hr $66,000 For irradiators with loadings less than 500,000 curies of ^{60}Co, pool chiller not needed and $24,000 subtracted from above estimates.	Same as above.
Control room and dosimetry lab	400 ft² at cost of $35 per ft². A 20% overhead construction fee is added to the calculated cost.	Morrison, 1985, Appendix A, no adjustments made to construction costs.
Fork lifts	Cost of forklifts estimated for each level of throughput (see Appendix C).	See sources listed in Appendix C.
Design and engineering of total facility ^{60}Co layout, product movement, utilization, etc. Varies widely with experience and knowledge base.	Estimated at 10% of facility cost.	Author's assumption.

Budget Item	Formulae and Assumptions	Source
Fixed maintenance	35% of total maintenance (total maintenance estimated at 3% of facility cost).	Author's assumptions.
Insurance and taxes	Unknown to author.	
Working capital	3 months' bills for labor, supplies, and utilities.	Author's assumption.
Fixed Labor	Annual Salaries: Plant Manager: $45,000 in United States. Maintenance person: $26,000 in United States Clerical: $18,200 in United States The above personnel only work one shift a day.	Morrison, 1985, Appendix U.S. wages reduced by 50, 75, and 87.5% for this analysis.
Land	3 acres for trucks to turn around, parking lot, landscaping, etc. at $5,000 an acre. (Same for all sizes of irradiators.) Actual land costs vary widely.	Author's assumptions.
Refrigerated warehouse	Space needed was based on storing four days' worth of throughput in case of unscheduled down times or shipping foul-ups. Product is stacked 15 feet high. 25% additional space allowed for aisles and other unusable space. Cost of $54 per ft^2, and a 20% overhead construction fee is added to the calculated cost. 165 ft^3/hr $75,000 330 ft^3/hr $150,000 660 ft^3/hr $300,000 990 ft^3/hr $450,000 1,320 ft^3/hr $600,000	Morrison, 1985, Appendix A.

Budget Item	Formulae and Assumptions	Source
Additional rooms and loading/unloading area	1,000 ft^2 for offices, mechanical room, bathroom, and lunchroom. (Same for all sizes of irradiators.) plus Loading and unloading area depends on throughput and was estimated as follows: 165 ft^3/hr 400 ft^2 330 ft^3/hr 400 ft^2 660 ft^3/hr 500 ft^2 990 ft^3/hr 800 ft^2 1,320 ft^3/hr 1,000 ft^2 Cost of \$35 per ft^2, a 20% overhead construction fee is added to the calculated cost.	Morrison, 1985, Appendix A (modified).
VARIABLE COSTS		
Supplies	4% of facility cost	Author's assumption.
Utilities	4% of facility cost	Author's assumption.
Variable maintenance	65% of total maintenance (total maintenance estimated at 3% of facility cost).	Author's assumption.
Variable labor	Annual Salaries per 8-hour shift: Radiation safety officer/quality control RSO/QC): \$35,000 in United States \$39,000 in United States Shift supervisor: \$35,000 in United States Shift supervisor not needed for two smallest irradiators.	Author's assumptions. U.S wages reduced by 50, 75, and 87.5% for this analysis.

Budget Item	Formulae and Assumptions	Source
Variable labor (cont'd)	Plant operator: $23,400 in United States Documentation (clerk): $18,200 in United States Product Handler: $19,500 in United States Number of handlers needed estimated in Appendix B. (No provision is made for wage differentials for second and third shifts.)	U.S. wages for product handlers reduced by 80, 90 and 95% for this analysis.

Annualized Fixed Costs

The capital recovery factor was used to estimate the levelized annual charge to recover the original investment (purchase price), plus the opportunity cost of the money spent to buy the asset, over the useful life of the asset. Asset assumed to have no salvage value.

$$\text{Annual charge} = K \times \frac{i(1 + i)^n}{(1 + i)^n - 1}$$

where:

K = original investment

i = interest rate

n = number of years of useful life

The useful lives for capital assets were assumed to be 15 years for initial ^{60}Co loading; 25 years for buildings and biological shielding; and 10 years for machinery.

The other fixed costs were treated as follows:

land   investment times interest rate

working capital   investment times interest rate

^{60}Co replenishment

fixed maintenance   } current cost items

insurance and taxes

fixed labor

$$\text{Unit cost} = \frac{\text{total variable + total annualized fixed cost}}{\text{throughput per year in kg}} \text{ in \$/kg.}$$

(Throughput per year was determined by number of hrs. operated per day times 250 days).

APPENDIX B. Number of Product Handlers Needed for Irradiators

Hourly throughput (kg.)	pallets/hr. 1/	worker/hr. needed per pallet	no. of handlers needed per shift to run irradiator 3/	no. of handlers needed to unload trucks for 1/2/3 shift operation 4/	total no. of handlers needed per day for 1/ 2/3 shift operation
1,500	3	.28 2/	1	1/2/3	2/4/6
3,000	5	.28	2	2/3/4	4/7/10
6,000	9	.28	3	3/5/7	6/11/16
9,000	14	.28	4	4/8/11	8/16/23
12,000	18	.28	5	5/10/14	10/20/29

1/ One pallet assumed to equal 675 kgs. Pallets/hr. rounded up to next whole pallet.
2/ Source (with modifications): Table 6 - "Labor and equipment time and cost to unload 900 hand-stacked cartons of fresh tomatoes and move to storage" in Mongelli, Feb. 1984, p. 15.
3/ Number of product handlers needed per shift rounded up to next whole person.
4/ See Appendix C for calculations. Trucks unloaded during 1 shift.

APPENDIX C. Number of Product Handlers Needed to Load and Unload Trucks

Hourly Throughput (kg.)	Pallets per hr. [1] 1 shift	2 shifts	3 shifts	Worker/hr. needed per pallet [2]	No. of handlers needed to load and unload trucks for 1/2/3 shift operation [3]	Forklift cost [4] $
1,500	3	6	9	.26	1/2/3	36,000
3,000	5	10	15	.26	2/3/4	36,000
6,000	9	18	27	.26	3/5/7	36,000
9,000	14	28	42	.26	4/8/11	36,000
12,000	18	36	54	.26	5/10/14	72,000

[1] Trucks are loaded and unloaded during one 8-hour shift.
[2] Source: Table 5--"Labor and equipment time and cost to transport 900 palletized cartons of fresh tomatoes from storage and hand-stack in trailer at packing plant" and Table 6 (see footnote 2, Appendix B) in Mongelli, Feb. 1984, p. 15.
[3] Number of handlers needed rounded up to next whole person.
[4] Cost of forklift is $18,000 each.
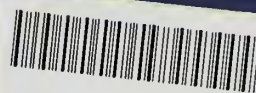
REFERENCES FOR APPENDICES

Deitch, Jerome, Jack W. Osburn, Jr. and Harry W. Ketchum. Cost-Benefits Analysis: Potential Radiation Sterilized Military Subsistence Items. BDC-788-09-71-002; U.S. Department of Commerce, Bureau of Domestic Commerce, March 1972.
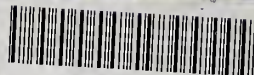
Jarrett, Robert D. Sr. "Isotope (Gamma) Radiation Sources," Preservation of Food by Ionizing Radiation, Vol. I, ed. Edward S. Josephson and Martin S. Peterson. Boca Raton, Florida: CRC Press, Inc., 1983, pp. 137-163.

Mongelli, Robert C. Marketing Fresh Tomatoes: Systems and Costs. Marketing Research Report No. 1137, U.S. Department of Agriculture, Agricultural Research Service, February 1984.

Morrison, R.M., "Economies of Scale in Single Purpose Food Irradiators" IAEA-SM-271/63 paper presented at the FAO/IAEA International Symposium on Radiation Processing, Washington, D.C., March 4-8, 1985.